

Exploration Life Support Overview and Benefits¹

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Abstract—NASA’s Exploration Life Support (ELS) Project is providing technology development to address air, water and waste product handling for future exploration vehicles. Existing life support technology and processes need to improve to enable exploration vehicles to meet mission goals. The weight, volume, power and thermal control required, reliability, crew time and life cycle cost are the primary targets for ELS technology development improvements. An overview of the ELS technologies being developed leads into an evaluation of the benefits the ELS technology developments offer.

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1. INTRODUCTION

ELS systems including air revitalization Systems (ARS), water recovery Systems (WRS), and waste management Systems (WMS) can provide capabilities needed to reduce the mass, energy and volume of future spacecraft and to decrease dependency on resupply.

ELS efforts focus on “closing the loop” to recover usable mass to decrease requirements for expendables, energy, volume, heat rejection and crew time, while at the same time providing a high degree of reliability. Additionally ELS identifies and develops improved ECLSS technologies to take advantage of modern materials and apply lessons learned. These improvements are essential to provide

required vehicle functionality with minimal vehicle resources.

Improvements range from addressing specific problems in existing technologies to completely new approaches to accomplishing life support processes. Regenerative processes will use new materials to better remove carbon dioxide and water vapor and contaminants. System integration will use waste products such as heat in one process to aid other processes needing heat to improve overall system efficiency. New catalyst materials will address air and water contaminants with technology that is more efficient without elevated temperatures improving safety. Better crew interfaces are being developed to address crew functions using lighter and cleaner processes with new combinations of materials.

Many life support technologies have been identified over years of concept developments that can potentially benefit future space vehicle life support systems. The ELS Project (and formerly the Advanced Life Support (ALS) program) has actively solicited ideas and developed the concepts from industrial, academic and government communities to identify concepts that are the most promising to provide significant benefits to life support systems. The result of that effort is captured in the ELS Project plan for developing new technologies to the readiness level at which the technology has been demonstrated to be capable of meeting exploration vehicle life support needs.

2. EXPLORATION LIFE SUPPORT PROJECT FORMULATION AND TECHNICAL CONTENT

ELS addresses a suite of enabling capabilities necessary to support human exploration missions as outlined in the U.S. Vision for Exploration [1]. The ELS Project was formulated based on three Exploration Systems Architecture Study (ESAS) [2] project recommendations, including atmospheric management, advanced air and water recovery systems, and habitability systems. Certain tasks under the ESAS recommended project area, Habitability Systems, were integrated into the ELS portfolio, including waste management (addressed in the original ALS program scope), hygiene systems and habitation engineering.

Technology development tasks for advanced thermal control (formerly within ALS and Explorations Systems Research and Technology (ESRT) programs) were combined into a new independent project entitled Thermal Control for Surface Systems. Other ALS tasks, including advanced food technology and human factors engineering, were integrated into other projects managed by the Life Sciences Program Office at NASA JSC. The thermal and food and human factors areas will not be addressed in this ELS paper except as related factors in calculating the integrated system mass of ELS concepts.

Project plans were developed in response to ESAS study recommendations and guidance provided by NASA

¹ 1497-Revision 3

Headquarters. The ELS Project Plan addresses the scope, organization and conduct of the life support Research & Technology Development (R&TD) efforts that will provide technologies to enable the exploration vision. The factors most relevant in determining technical content for inclusion within the plan include:

- Is a specific technology development effort required for either the Crew Exploration Vehicle (CEV), Lunar Surface Access Module (LSAM) or Lunar Outpost (LO) vehicles or habitats?
- Can the technology reach Technology Readiness Level (TRL) 6 in time to support CEV, LSAM or LO Preliminary Design Reviews (PDRs)?
- Is the technology expected to provide a significant improvement over the State of the Art (SOA)?
- Does it fill an exploration mission requirement not addressed by current technologies?
- Does the technology require long lead development to make it available for later exploration missions such as the LO or Mars missions?

A summary roadmap for ELS, reflecting emphasis within the existing portfolio is depicted in Figure 1. The roadmap provides a time phased, mission oriented, graphical portrayal of the ELS project current R&TD portfolio and emphasis. The focus of efforts is in four technical elements ARS, WRS, WMS and Habitation Engineering, with a systems engineering support component that includes System Integration, Modeling, and Analysis (SIMA), integrated testing, and flight experiments. Specific tasks and focus areas for each technical element is given in the following sections.

The content of the ELS Project was established related to exploration goals and the time criticality of life support functionality and limitations in technology development budget. The rationale for the current project content and the way specific technologies contribute to near term CEV, LSAM and LO missions was presented at the July 2006 International Conference on Environmental Systems (ICES) [3]. In December 2006 NASA released the results of the Lunar Architecture Team studies. The approach to lunar missions to focus on building a Lunar Outpost as a first priority changed the likely LO PDR date to 2013 as shown in Figure 1.

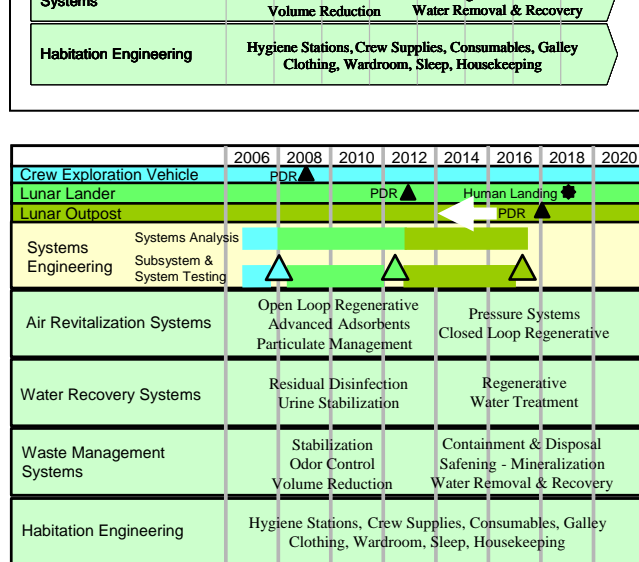


Figure 1 - Summary Roadmap for Exploration Life Support Research and Technology Development

The current ELS portfolio was developed by making decisions on the relative merits of new concepts for addressing life support functions and providing funding to those with significant promise. The change in ELS Project focus described in the ICES report [3] was the latest in evaluations of the merits of technology development projects and directly related to the better definition of exploration goals that the Constellation (Cx) program has provided in 2005 and 2006. Each year the prior ALS element (of the Human Systems Research Technology (HSRT) Program) made similar decisions on technology projects. The assessments are based on a combination of the best analytical data available on the proposed technologies, the relevance to the likely exploration plans and the cost versus benefit of the technology. In future years the ELS portfolio is expected to be reviewed and decisions made on future content with more participation from the Cx organization to ensure that future technology investments are relevant to exploration goals.

ELS technologies address the spacecraft and surface habitats that require improved and/or additional capabilities to accommodate new environments, longer periods of service, unique mission operations and configurations.

Some advanced technologies will be better than those used in existing vehicles regardless of the mission length because they provide improved functionality with less resource requirement and more robust solutions to life support requirements. Others will trade well when mission durations are longer than early exploration missions and/or the expense of providing consumable resources is too high to allow the existing technologies to be used.

ELS technical maturity and mission applicability

ELS technologies vary in technical maturity and the degree to which they contribute to system closure. Simple technologies may be best for the short duration CEV and lunar sortie (or LSAM) missions. More sophisticated technologies that recover more of the vehicle waste products

are required for the longer Lunar Outpost and Mars missions.

Planning for including ELS technology products in Cx vehicles has been addressed in meetings with Cx lead life support engineers. More recently the CEV contractor Lockheed Martin has been involved in meetings with life support groups to understand the link of ELS technology development to the CEV program.

Cx Program efforts have resulted in much better definition of the missions that exploration vehicles will accomplish in the future. The first vehicle (the CEV) mission has been defined at a top level and efforts to better define the mission are underway. Related to the CEV mission, definition concepts for a LSAM mission and a LO mission have been defined. The CEV vehicle has also defined a set of technology that will be included in the design of the vehicle (given no development problems force a change in technologies).

The ELS Project also addresses the analytical efforts of evaluating potential technologies for operational capabilities and potential benefits. The results of some of those studies will be summarized in section 7.

3. AIR REVITALIZATION SYSTEMS (ARS)

Air revitalization functions addressed include carbon dioxide partial pressure control, trace volatile organic carbon (VOC) concentration control, particulate matter removal, atmospheric gas storage and distribution, resource recovery, and supporting infrastructure. Candidate technologies are summarized in Figure 2.

Technology development addressing functional needs for the CEV includes vacuum swing adsorption processes for carbon dioxide pressure control, expendable and regenerable VOC adsorbents and improved carbon monoxide oxidation catalysts for control of trace VOC concentration; high pressure, cryogenic atmospheric gas storage and distribution systems with minimum boil-off; and supporting infrastructure including improved blowers, valves and process monitoring and control instrumentation with well-developed robust design practices.

Target Technologies	Mission	CEV	LS	LO
<u>Carbon Dioxide Partial Pressure and Humidity Control</u> — improved chemisorbent media, improved physical adsorption media, novel adsorbent media substrates and bed packing geometries, vacuum swing adsorption processes, combined vacuum/temperature swing adsorption processes.		√	√	√
<u>Control Trace VOC Concentration</u> — regenerable adsorption media, novel adsorbent media substrates and bed packing geometries, improved thermal oxidation reaction designs, novel catalyst substrates and reactor geometries, highly efficient recuperative heat exchanger designs.		√	√	√
<u>Atmospheric Gas Storage, Supply, and Distribution</u> — storage tank recharging equipment; high pressure, cryogenic, and supercritical storage; high pressure Oxygen production.		√	√	√
<u>Supporting Infrastructure</u> — improved blowers, valves, and process monitoring and control instrumentation; well-developed robust design practices.		√	√	√
<u>Particulate Matter Removal</u> — inertial separation (10 microns), electrically-enhanced filtration (<0.1 micron), electrostatic precipitation (<0.1 micron), and HEPA filtration (0.3 micron) system designs.			√	√
<u>Resource Recovery, Storage, and Recycling</u> — carbon dioxide reduction processes to methane and carbon products.				√
<u>In-situ Resource Utilization (ISRU)</u>				√

CEV = Crew Exploration Vehicle; LS = Lunar Sortie; LO = Lunar Outpost

Figure 2 – Air Revitalization Technologies

The CAMRAS technology for CO₂ removal and moisture control prototype unit is shown in Figure 3



Figure 3 – The Carbon Dioxide and Moisture Removal Amine System Prototype Unit and Test Chamber

For lunar sortie missions, all identified technologies are applicable except for resource recovery and ISRU. Particulate matter control will be important starting with lunar sortie missions due to concerns related to lunar dust.

All identified ARS technology candidates are applicable to address life support needs for LO and future long duration missions.

4. WATER RECOVERY SYSTEMS (WRS)

WRS addresses potable water supply and recovery of water from waste fluids. To support CEV and lunar sortie missions, a set of immediate technology development needs have been identified. They include:

- Urine pretreatment system - A suite of potential urine pretreatment agents has been identified. In FY06, a WRS ELS team identified the most promising of these agents. Work to evaluate the most promising candidates for efficacy, compatibility with the waste collection system, and compatibility with physicochemical and biological systems is underway.

- **Disinfection systems** - A suite of potential disinfection agents and methods have been identified for further development. The primary application is as a biocide in the potable water storage system. A task was initiated in FY06 to examine the most promising options and begin development of technology.
- **Short Duration Mission Water Recovery Systems** - Technology approaches for small scale water treatment systems include single-phase flow-through units employing ion exchange, adsorption, multi-filtration and/or osmotic filtration. The systems may utilize consumable media and could be stowable. Systems under development by other agencies for expeditionary warfare and emergency survival water supplies will be considered, as appropriate.

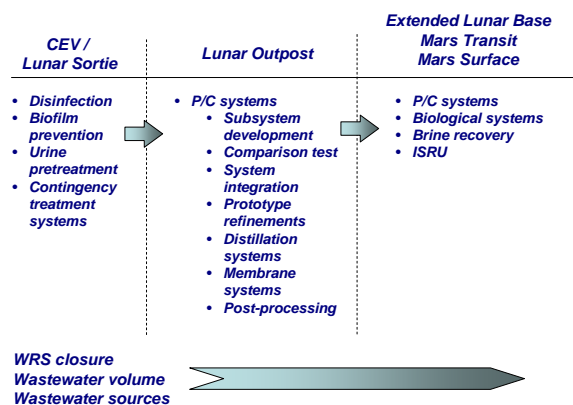


Figure 4 – Water Recovery System Technologies

To prepare for intermediate and long duration missions such as lunar outpost, technology development needs have been identified to enable recovery of potable water from waste water. These tasks include:

- **Distillation technologies** - A variety of systems with potential to improve power consumption of distillation systems are currently in development are being continued. These include: Vapor Phase Catalytic Ammonia Removal (VPCAR) (a combination of wiped-film rotating disks for distillation and catalytic ammonia removal); the Cascade Distillation System (CDS) (a multi-stage distillation system expected to have lower power and volume requirements); Direct Osmotic Concentration (DOC) (a membrane based technology that uses osmotic pressure and membrane distillation to purify wastewater); and the Advanced Vapor Compression Distillation Water Recovery System (AVCD WRS) (an extension of the ISS WRS that capitalizes on lessons learned and ISS technology investments).
- **Improved post-processing systems** - Ambient temperature technologies that utilize photolysis, photocatalysis, thermal catalysis and optimized ion exchange are currently under investigation.

- **Microgravity assessments** - Assessments of microgravity operations to increase the operational reliability of WRS systems on transit missions. This task will evaluate the candidate primary water processing systems for microgravity and partial-gravity compatibility through ground/aircraft testing and analyses.

5. WASTE MANAGEMENT SYSTEMS (WMS)

WMS technologies address the need to manage waste aboard future spacecraft for volume reduction, stabilization, drying, water recovery, safening, mineralization, storage and disposal.

- **Volume Reduction** - Volume reduction is principally accomplished by compaction. For near term missions, hand operated and automated mechanical compactors are under development. For surface missions, a plastic heat melt compactor is under development.
- **Waste Stabilization and Safening** - A primary target of stabilization technology will be safening of feces. Various toilet and alternative feces collection devices will be considered in conjunction with drying technologies such as freeze and vacuum drying. The vacuum available in space and on the surface of the moon will be utilized for near-term short duration missions (CEV and lunar sortie) since the waste water will not need to be recovered for that mission. Improved methods of collecting human waste considering the extremely volume and weight limited and relative short duration CEV and LSAM missions are being developed in connection with habitability engineering. Modern materials are being used to improve bag technology to address the human waste collection, odor control, and vacuum connection for drying and waste compaction. Current developments to improve the bag feces and urine collection concept flown on Apollo use ducted air to aid the collection and odor removal process.
- **Alternative drying methods** are also under consideration for stabilization of other wastes including trash, with and without recovery of water - Technologies include microwave heated drying and air drying. These tasks will include modeling removal/evaporation of moisture from the waste and its condensation for storage or venting to space, including compatibility of condenser systems for micro and hypo gravity.
- **Mineralization** - Mineralization technologies are the most advanced technologies for safening and stabilizing waste as well as recovering resources and volume reduction. Mineralization technologies include incineration, hydrothermal oxidation, pyrolysis, and composting. Mineralization technologies convert waste to small basic molecules such as carbon dioxide, water, methane, and inorganic minerals. The residuals from mineralization are sterile, stable and minimal in volume.
- **Storage and Disposal** - New development efforts are planned for containment technology and disposal technology. Containment technology includes

development of containers for disposal of waste on a planetary surface designed to last for extended periods of time. Containers would need to be designed such that there would be no harmful interaction with the space craft and no impact to a planetary surface.

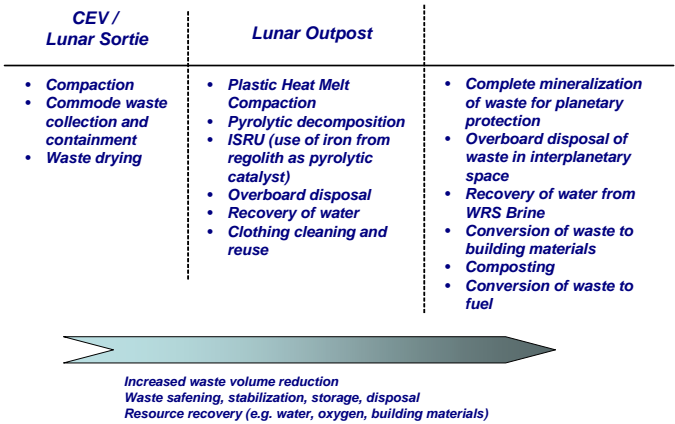


Figure 5 – Waste Management System Technologies

6. APPROACHES TO ESTABLISH THE BENEFITS OF ELS TECHNOLOGIES

The benefits of ELS Technology over existing technologies can be assessed in many ways. Engineering assessments can establish benefits of operation such as reduction or elimination of the need for consumables. Engineering assessments of the basic technology can establish the relative complexity of a technology. Trade studies can be performed to assess the relative merits of technologies that address the same life support function. Test of technologies can establish the performance characteristics of a technology and provide quantifiable data. Analytical calculations can establish the way a technology can operate to meet a given life support function for a given set of mission constraints.

To establish the advantages of new technology versus existing or proven technology the SIMA element of the ELS Project has collected theoretical and empirical information on technology options and integrated that information into analytical modeling programs to establish a way to calculate the resources required to operate current and new technologies. SIMA models use the theoretical information of each technology combined with the best available design and test data to calculate the resources required to operate the technology. When development data on engineering or prototype unit design and test data becomes available, the SIMA models are updated to refine models and improve the accuracy of predictions.

The analytical techniques have evolved over the years that integrate technologies into functional life support systems so that the overall resources required to provide a life support function using combinations of life support technologies can be evaluated. Factors have been established to calculate the effect of weight, power, thermal control and crew time for the combined system.

ELS has evaluated techniques for trading technology options and has determined that the concept of Equivalent System Mass (ESM) is best suited for life support technology evaluation. The ESM concept uses basic technology attributes combined with a given mission scenario and vehicle infrastructure to calculate the amount of vehicle mass associated with providing the life support function. The vehicle infrastructure includes the related life support equipment needed to operate the technology; the consumables needed to operate the combined life support suite of equipment; the power and thermal support required. The ELS equipment and required supporting equipment are combined and used with factors for the mission mass associated with supporting functions to calculate an equivalent mass for a given mission for an ELS technology option (the ESM).

The basis for the ESM calculations has been documented in several SIMA documents. The Baseline Values and Assumptions Document (BVAD) [4] and the ALS database establishes the data used in SIMA analytical models and calculations. Reference mission data has been developed and documented in the ALS Reference Missions to provide a target set of mission description data. A collection of requirements that the ALS technologies were to address and thus are used in sizing assumptions are provided in the ALS requirements Document [5]. The candidate technologies considered in SIMA calculations is maintained as the ELS technologies List [6].

The combination of technology data and mission parameters allows the calculation of the ESM for a specific set of technologies and a specific mission. Changing any of the technologies used in the system or the mission to be assessed changes the ESM.

Baseline for Comparison of ELS Technologies

To evaluate the relative merits of technologies, a set of baseline technology is assumed to establish a basis of comparison.

Establishing the State-of-the-Art (SOA) - SIMA studies use data from shuttle and ISS life support systems for the well established performance data they provide to compare against the performance of new technologies. A baseline ESM is calculated assuming shuttle or ISS technologies. Using the same mission scenario; the resources required when ELS technologies are used are calculated resulting in an ELS ESM.

The ELS Metric - For the Mars scenario, ESM calculations were done yearly for the best combinations of technologies. The ESM for the baseline divided by the ESM for ELS technologies was established as the ALS metric [7]. That metric calculation formed the basis for calculating the relative benefits for ELS technologies and the basis for monitoring the improvement that can be provided using

ELS technology.

The new ELS metric for CEV and LSAM relates the performance of shuttle technologies versus newer technologies. Technologies used in the shuttle are used for comparison because those are suited for relatively short duration missions.

For the LO missions, ISS technologies are considered to establish the baseline as relevant ELS long duration mission technologies. ISS technology assumptions include planned and current ECLS technologies. The planned ISS technology is mature via ISS high TRL level testing and preparations. Thus calculations using data on planned ISS technologies results in relatively accurate ESM calculations. ISS technologies that are planned but not yet implemented on ISS include the ISS WRS and Sabatier technologies. Thus calculations using the ISS baseline anticipate that those planned technologies will be implemented on ISS and that they will perform as expected based on ground testing. The ELS community assesses the degree of uncertainty based on engineering judgment of the effect of the environment on ELS processes.

Technology Maturity Considerations - The calculation of an ESM uses the best available data on a given technology. Space Shuttle and International Space Station technologies have demonstrated performance in the shuttle and ISS environments. A level of engineering judgment is required to determine when a mission scenario is so different than a shuttle or ISS mission as to require alteration of the way ESM is calculated for those technologies. For example: if shuttle technology is used for a lunar sortie mission an assessment must be made related to the environment of the lunar mission versus the shuttle low earth orbital environment. The lunar environment is more extreme for thermal and includes potential dust sources that could change the performance of life support equipment. Thus using shuttle performance data directly to calculate the ESM for a lunar mission involves a level of uncertainty.

ELS technologies early in technology development and may have only basic concept validation data to support calculating the performance to be expected from that technology. As the technology is developed to more mature levels and testing establishes the capabilities of the technology to provide for its intended life support function the calculation of resources required is more accurate. When the technology reaches the level of having a prototype (relevant to expected vehicle needs) manufactured and tested in an environment representative of the vehicle in which it will function (TRL-6) the calculation of resources required to operate the technology becomes more accurate.

While the ESM calculation is based on the best data available, it must be qualified based on the maturity of the technology. ESM calculations are still the best available means for comparing technologies.

7. ELS BENEFITS AS QUANTIFIED IN SIMA STUDIES

Many SIMA studies have been conducted to establish then compare the ESM of potential ARS, WRS and WMS technologies. Those studies have evaluated combinations of life support technologies that start with a baseline of technologies then evaluate combinations of ELS technologies to address the same functions for the same mission scenarios. Thus the calculated ESM for options can be directly compared and the relative benefit can be established. (Highlights of ELS benefits are emphasized in blue).

SIMA studies have focused on Mars missions for past metrics calculations. However, many other studies have been conducted to determine when technologies become better for ESM than current technologies. Those studies have determined that for air technologies CAMRAS is better for ESM than LiOH when mission duration exceeds around 2 weeks. Regenerative water systems become better when mission durations are over 4 weeks. WMS benefits have been calculated for a Mars mission as shown in Table 1.

Table 1 – WMS Benefits for a Mars Mission

Waste Management - Benefits				
Mission Cost (measured by Equivalent System Mass - ESM) Reduction				
A Comparison of International Space Station (ISS) Technology with Advanced Life Support (ALS) Technology. For 1000 day Mars mission with 6 crew.				
Name	ISS ESM	ALS ESM	delta	comment
Waste (clothing, feces, food packaging, scraps, etc.) safener - e.g. container vs. mineralizer	3,933	1,000	2,933	assume containers for ISS - processor for ALS
Waste Disposal on Mars surface	5,899	1,000	4,899	savings on return propulsion
Water in feces and waste	2,000	500	1,500	water saving vs cost
Clothing	6,780	1,200	5,579	clothing washer
Compaction	3,000	1,000	2,000	assume crewed vol=200 kg/m ³ , ISS is 1/2 compact by hand

ESM benefits have been established for specific scenarios and have shown the ESM benefit of ELS technologies. SIMA studies will continue to use the analytical techniques developed to assess new mission and technology combinations as they are defined.

The 2006 ELS metric has added CEV, LSAM and LO scenarios. The shuttle technology ESM was calculated as the SOA for CEV and LSAM missions. ESMs were also calculated for selected ELS technologies using the CEV and LSAM scenarios. Assumptions for the mission length have been refined based on recently released Cx data. However, LSAM and LO missions are still in formulation phase; thus the assumptions for the LSAM mission are more subject to change. Some assumptions for the metric calculation of

2006 are given in Table 2.

Table 2 – Near Term Exploration Mission Parameters used in the 2006 ELS Metric Calculation (the LSAM mission has subsequently been defined to be 7 days (TBR))

Vehicle	Total Crew Cabin Volume (M3)	Mission Duration (days)
CEV	29.4	18
LSAM	16.7	5
LO	39.6	181

The ELS calculation for the CEV assumed some waste water recovery via Volatile Removal Assembly (VRA) and Multi-Filtration (MF) as established technologies. (Other studies described in following sections evaluated more recent ELS technologies.) The LSAM study assumed the Carbon Dioxide and Moisture Removal Amine System (CAMRAS) for CO₂ and humidity control and storage for water and waste systems. The LO ELS technologies also used CAMRAS.

For the set of ELS technologies used in the 2006 metric the benefit in ESM was calculated and determined to be as summarized in Table 3. The calculated ESM benefits related to ELS technologies can significantly impact total mission planning.

Table 3 – ELS Metric for CEV, LSAM and LO

Cx Vehicle	Baseline ESM(kg)	ELS ESM(kg)
CEV	3320	2260
LSAM	2320	1980
LO	14330	9310

In addition to the yearly ELS metric, many more specific technology assessments are performed to address relative merits of other sets of technology.

CAMRAS Study Results - The technologies baselined by NASA and the CEV Contractor (Lockheed Martin) for the CEV vehicle have been assessed in a 2006 SIMA study specifically on the CEV. That study calculated the benefits of the CAMRAS technology for not only the air revitalization but also the effects of the elimination of the need for humidity removal via a condensing heat exchanger (CHX). The study focused on the CO₂ and humidity removal and water required by the crew.

Elimination of the need for a CHX means that the temperature control for the CEV vehicle doesn't have to provide the low temperature required to condense moisture from the air. The temperature control requirement is based on avionics cooling needs and on the need to collect only sensible heat loads from the crew (versus the lower temperature required to condense moisture). The minimum temperature required to be returned to the cabin is increased by around 11 degrees C. At that higher return (or radiator outlet) temperature, the heat rejection required can be accomplished using less radiator surface area for a given

radiative environment. Calculations established that the penalty for heat rejection can be lowered from 75 to around 70 kg/kW. With peak vehicle loads that the radiator system has to reject of around 6 kW that benefit translates to a mass savings of around 30 kg. It also addresses a critical limitation of surface area on the CEV by reducing the area required for heat rejection.

Calculations of the CEV ESM using the baseline shuttle ECLS technologies (LiOH + water tanks results in an ESM estimate of 515 kg. Calculations of the CEV ESM using the ELS + water tanks) (the CEV baseline) results in an ESM estimate of 473 kg.

For the short duration of the CEV mission of 18 crewed days a significant benefit of around 70 kg is achieved using the CAMRAS technology.

The mission flexibility is also increased significantly since the CAMRAS is not constrained by consumables launched with the mission. Thus if CEV missions are increased in length the CAMRAS technology will be even more beneficial.

8. QUALITATIVE BENEFITS OF ELS TECHNOLOGIES

The basic functions of ELS technologies have been presented. In the start of this section the analytical assessment that allows quantitative calculations was described along with some examples of the results of such calculations. In addition to the benefits that can be calculated, there are many benefits that relate to attributes and operational improvements. A combination of the quantifiable and qualitative benefits is used to evaluate the relative benefits of technologies.

The factors that contribute to technology selection were a

The CO₂ removal and reduction trade study [6] combined the assessment of factors with reference mission assumptions to evaluate system integration combinations of technologies.

That CO₂ study also evaluated factors that directly impact ESM calculations that have to be assumed. Those factors relate to mission parameters and goals and operations to be conducted.

- Mission Parameters - number of crew, mission duration, number of Extra-Vehicular Activities (EVAs), sun/shadow duration ratio, etc.
- Duty Cycles - some ECLS functions, such as the CO₂ removal subsystem, should ideally be operated continuously. Other functions such as oxygen generation, may be better operated only during times when power is most readily available due to the power needed by that function

- Crew Metabolic Requirements and Products
- Redundancy
- Supporting Technologies
- Mission environment (surrounding atmosphere or vacuum, gravity field, thermal)
- Vehicle size (affects the volume of the atmosphere and thus transients)

ARS Qualitative benefits - The CAMRAS has been addressed in the SIMA CO₂ trade study for quantifiable benefits. In addition, the CAMRAS offers the benefits of:

- 1) A regenerable process that can continue for the duration of a mission (confirmed by CAMRAS test results). Thus mission planning is not constrained by CO₂ removal since consumables are not used.
- 2) The volume needed to accomplish CO₂ and humidity removal is the lowest of any technology option. Thus the extreme volume constraints of the CEV and LSAM vehicles are best addressed by the CAMRAS technology.
- 3) Thermal control for CAMRAS is not needed since the technology links the heat producing adsorption bed to the alternate layer endothermic desorbing bed layers. This improves the desorption process by providing a source of heat and eliminates the need for active cooling of the heat producing adsorbing side.
- 4) The CAMRAS technology is reasonably mature since the amine has been tested and the prototype unit has been developed and has passed initial breadboard and integrated testing.

The Sorbent Based Air Revitalization (SBAR) system has many of the same attributes as the CAMRAS. It also offers these benefits:

- 1) The zeolite adsorbent used is benign and readily available
- 2) The absorbing material does not degrade over use

However, the SBAR will be larger than the CAMRAS and may require higher vacuum to operate efficiently.

New Trace Contaminant Control (TCC) materials address the concern that activated carbon used in current systems may not be able to function after exposure to vacuum. Such exposure may happen as part of the CEV requirement that the CEV be functional after exposure to vacuum related to potential contingencies.

Atmospheric storage technologies address the potential need to efficiently store atmospheric gases. Improvements may provide cryogenic storage that offers significant reductions in weight and volume needed for the required amount of O₂.

Particulate removal developments address the lunar dust problem for dust that escapes early containment processes and enters the cabin of the exploration vehicles. Existing

filtration techniques may be inadequate to address lunar dust filtration due to the significant portion of lunar dust that is extremely small, has fractured surfaces and is chemically reactive making it hazardous for crew health.

More advanced CO₂ removal and reduction technologies address the need to further “close the loop” for longer missions. These technologies recover both the O₂ in CO₂ and some of the H₂ waste produced in the electrolysis of water used in providing O₂ for the vehicle. Less water and atmosphere consumables are required since a significant portion of the CO₂ and H₂O is recovered and used again. This combined with recovery of humidity directly from cabin air is essential for dramatically reducing consumables required for long missions.

WRS Qualitative benefits - The benefits derived from WRS technology being developed for the early CEV and LSAM missions are principally qualitative. However, the benefits from the water recovery technologies relevant to longer missions are quantitative and extremely important for reducing water needed for those missions. Indeed long duration missions may not be achievable without recovery and recycling of water resources.

The water recovery technologies viewed as best for long missions could be used effectively for short missions. Using these technologies would add commonality of technologies with later exploration vehicles and would save development cost. However, trade studies that are very critical for mass and power for early vehicles indicate that the regenerative technologies are best only for missions slightly longer than the CEV and LSAM missions.

Urine pretreatment developments are looking for more acceptable additives than the Oxone used in present ISS systems. Oxone is toxic and safety procedures needed to handle it and operate the system with it are burdensome to ground and crew personnel. This research has identified several candidates that could be slightly less toxic and even more effective at stabilizing urine so that it can be stored for the duration of exploration missions safely. The new pretreatment chemicals may also be more compatible with later water recovery technologies thus making water recovery for LO and beyond missions more achievable.

Disinfection technology research is expected to lead to a disinfectant for stored and recovered water that is more effective at minimizing biological growth and more compatible with crew consumption. Iodine used in prior US water storage systems requires an Iodine Removal Assembly (IRA) to remove it from water before crew consumption. This research expects to identify disinfectants that do not need to be removed before crew consumption thus eliminating the need for the IRA. Long term stability of the disinfectant is another goal that will potentially eliminate the need to reintroduce biocides during missions.

Contingency water resources may be needed during

exploration missions. Development of a space version of ground technology that can recover the water from urine via membrane separation may address the need for water during contingencies. Such a technology could provide needed water without the need for heavy contingency water storage.

Point of Use (POU) filtration can potentially address the need for control of microbial content in water sources without biocides. If successful, the POU concept can establish that a filter can address microbial control at the location where water is dispensed. POU technology is derived from commercial filters and is also evaluating new technology for POU filter materials. While it may still be required to control microbial growth in storage vessels, the POU technology may reduce the need for biocide addition and/or microbial monitoring. Thus the POU approach may lead to purer water for the crew at little expense and also significant operational improvements (by eliminating the need to inject biocides).

Longer exploration missions require water recovery and reuse due to the large amount of water required to meet crew needs. The distillation technologies provide the primary means of recovering water from waste urine, humidity, and hygiene water. SIMA studies have shown that the LO scenario can save almost 5000 kg (Table 2) of mission mass when WRS technology is implemented (versus ISS WRS technology).

Improved post processors should be able to provide potable water without high temperature processors thus improving safety and reducing power required.

Waste Management System Qualitative Benefits - The general benefit of waste management capabilities is to reduce mission cost and satisfy mission requirements. WMS efforts address:

- Crew health and safety - The longer duration of future missions (without access to routine resupply and disposal return missions) needs improved waste management to assure crew safety. Detailed requirements in this area are not yet established but expected requirements include safening. Drying is the minimum level of safening and mineralization can also dry waste and may provide better protection from hazards.
- Crew quality of life - Odor, clutter, and other qualities of waste can negatively affect crew outlook and performance. It is assumed that this requirement supports the need for improved management of waste via deodorization, compaction, drying, and mineralization.

WMS addresses these exploration needs via:

- Volume Reduction - Storage space for wastes is very limited on space vehicles. Volume reduction or compaction saves valuable space. Compaction minimizes volume occupied by waste and thereby recovers volume.

Used in conjunction with heat, compaction can also recover water and stabilize waste.

- Water Removal and Recovery - Many wastes such as concentrated water brines or food scraps contain substantial quantities of water that can be recovered. Water removal and recovery contributes to closure of the water loop and also results in reduced volume. Microbiological and pathogenic activity is inhibited in dried residue thus protecting crew health.

- Safening and Stabilization - Safening is processing the waste to make it safe for the crew or harmless to planetary surfaces. Once safened, stabilization assures that the waste does not change its state. Mineralization recovers resources such as water and decreases waste volume. Depending on extent of processing, mineralized products are rendered partially to completely biologically nonhazardous and inert.

- Containment and Disposal - Contained waste is isolated from the crew and the external environment. Waste is disposed when the final act of handling or accessing is completed. Disposal can be onboard, overboard, in space, and on planetary surfaces. Containment of waste protects the crew from physical, chemical, and biological waste hazards onboard the spacecraft. It also protects planetary surfaces from contamination with microbes and biomarkers and protects Earth from back-contamination. Overboard disposal eliminates the need to provide stowage volume, eliminates the need to process waste to protect the crew, and reduces propulsion needs.

- Resource Recovery - Waste can be processed for reuse for the initial function, or it can be converted to new useful substances. Examples include cleaning clothes for reuse, converting waste to minerals for use as food growth nutrients, and pyrolyzing waste to form activated carbon. Resource Recovery reduces the cost of resupply of items needed for other processes.

9. CONCLUSIONS

The ELS Project addresses the need to develop new technologies for exploration missions. Technologies being developed will contribute to current and future needs of exploration vehicles. Technologies best suited for the CEV and LSAM missions are now emphasized in the ELS Project. However, those needed for LO and subsequent missions are also included to address long duration mission needs.

The processes of evaluating ELS technologies for the benefit they offer involves both quantitative and qualitative assessment processes. Current studies have established the benefit of ELS technologies in terms of ESM using the best data and techniques available. ESM calculation allows comparison of technical options with mature technology options. Such ESM studies have resulted in selection of the

CAMRAS technology as the preferred way to address CO2 and humidity removal for the CEV and LSAM. Efforts continue under the ELS Project to develop technologies to more maturity to improve the reliability and accuracy of ESM calculations.

A combination of the ESM calculations and qualitative benefits for ELS technology must be used to select the life support technology best suited for exploration missions. Some of the factors that will contribute to the selection have been established in this report.

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11. BIOGRAPHY

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13. ELS ACRONYMS

ACRRS	Advanced Carbon Dioxide Removal and Reduction System
ALS	Advanced Life Support
ALSSAT	Advanced Life Support Sizing Analysis Tool
ARS	Air Revitalization System
AVCD	Advanced Vapor Compression Distillation
BVAD	Exploration Life Support Baseline Values and Assumptions Document
CHX	Condensing Heat Exchanger
CAMRAS	Carbon Dioxide and Moisture Removal Amine System
CDS	Cascade Distillation System
CEV	Crew Exploration Vehicle
CHX	Condensing Heat Exchanger
Cx (P)	Constellation (Program)
DOC	Direct Osmotic Concentrator
ECLSS	Environmental Control and Life Support System
ELS	Exploration Life Support
ESRT	Exploration Systems research and Technology
ESCG	Engineering and Science Contract Group, Houston, Texas
ESM	Equivalent System Mass
EVA	Extravehicular Activity
HEPA	High Efficiency Particulate Air (filter)
ICES	International Conference on Environmental Systems
IRA	Iodine Removal Assembly
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JSC	NASA Johnson Space Center
KSC	NASA Kennedy Space Center
L	liter
LiOH	Lithium Hydroxide (canister)
LMSO	Lockheed Martin Space Operations, Houston, Texas
LO	Lunar Outpost
LRM	Lunar Reference Mission
LSAM	Lunar Surface Access Module
NASA	National Aeronautics and Space Administration
NSCORT	NASA Specialized Center of Research and Training
NWR	No Water Recovery
PDR	Preliminary Design review
POU	Point of Use (filter)
RD	Advanced Life Support Requirements Document

RMD	Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document
R&TD	Research and Technology Development
SAVD	Solid Amine Vacuum Desorption
SBAR	Sorbent Based Air Revitalization
SCWO	Super Critical Water Oxidation
SIMA	Systems Integration, Modeling, and Analysis
SOA	State-of-the-Art
STS	Space Transportation System (a.k.a., “Shuttle”)
TCCS	Trace Contaminant Control System
TRL	Technology readiness Level
UV	Ultraviolet
VOC	Volatile Organic Carbon
VPCAR	Vapor Phase Catalytic Ammonia Removal
VRA	Volatile Removal Assembly
WMS	Waste Management System
WRS	Water Recovery System